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REVIEW PAPER

Revisiting the Potential use of Biochar Amendment in Agricultural Soils: A Review

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ABSTRACT

Biochar is an emerging soil amendment that has gained significant attention in the past two decades. Besides other benefits for the soil and the entire environment, biochar plays a remarkable role in improving the soils for agricultural production. Contrary to other sources of organic matter, biochar is composed of a larger proportion of aromatic carbon (C), which gives it high biodegradability, high organic carbon (OC) content, and concentration of plant nutrients. This makes biochar a high-quality source of organic matter. Due to the properties possessed by biochar, once applied to the soil, it will tend to improve the soil properties which will consequently modify the properties to better suit the crop production. Therefore, this review provides insights into how the chemical, physical, and biological soil properties are affected following the biochar application.

HIGHLIGHTS

- Biochar improves soil physical, chemical, and biological properties, leading to enhanced soil fertility and agricultural productivity.
- Biochar it effectively immobilizes and adsorbs both organic and inorganic pollutants, reducing their uptake by crops.
- Biochar contributes to long-term carbon storage in soils, aiding climate change mitigation efforts.
- Biochar promotes microbial diversity and activity, thereby supporting soil biological functions and resilience

Keywords: Biomass, soil pH, soil microorganisms, organic and inorganic pollutants, mineralization, immobilization, soil nutrients

According to Nair *et al.* (2022), biochar is a carbon-rich substance that is created during the process known as pyrolysis, which is the thermochemical breakdown of biomass at a temperature of roughly

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≤700°C without or with a limited supply of oxygen. Biochar is super charcoal produced by heating any biomass without oxygen, according to definitions provided by other authors (John 2021; Tanure *et al.* 2019; Mwadalu *et al.* 2022). The biomass used are sourced from various sources such as corncobs, rice or wheat straw, potato or soy hay, and husks or stalks. About 40% of the pure carbon that was once present in the biomass is burned away along with cellulose, lignin, and other non-carbon components. The European Biochar Foundation has recently described biochar as the emerged product of pyrolysis of plant biomass materials that yield a porous, carbonaceous substance that is used in industrial processes to either replace fossil carbon or store carbon for extended periods. It's not designed to be burned to produce energy (Conte *et al.* 2021).

According to Schmidt and Noack (2000), biochar has a higher amount of aromatic carbon such as lignin than soil organic matter. This is how biochar differs from other organic matter: it has ideal concentrations of micro- and macroelements and high levels of total and organic carbon in addition to its high biodegradability capacity (Malińska 2012). Hernandez-Soriano *et al.* (2014) also report that biochar has a high surface area, and a high quantity of functional groups with longitudinal pores ranging in size from micropores to macropores, as well as a high porosity. Theres exists multiple varieties of biochar, including but not limited to wood, straw, shell, bamboo, sludge, manure, and numerous additional types. The pyrolytic temperature and the biochar's composition are the reasons for this classification (Jindo *et al.* 2014). The components, volatiles, and ash content of the final biochar are all determined by the type of material employed in its manufacture (Ippolito *et al.* 2015).

Many scholars report the ability of biochar to improve the quality of soil. Applying biochar can increase the amount of organic matter in the soil, which raises soil fertility (Wei *et al.* 2019; Alkharabsheh *et al.* 2023; Khan *et al.* 2025; Shao *et al.* 2024). Biochar can contain some nutrients depending on the material used and the pyrolysis temperature used in its production, and because of its highly porous structure, it can also help the soil retain nutrients. Additionally, according to Muh *et al.* (2021), biochar can raise soil electrical conductivity and nutrient level while decreasing the acidity of the soil. These changes accelerate the availability of nutrients in the soil. According to certain data, plants may have less access to trace elements when using biochar. The level of As, Cd, and Cu in plant shoots was found to have significantly decreased by Osayi *et al.* (2014) following the application of biochar. However, the availability and uptake of heavy metals by the plant varied based on the metal and the rate of biochar application. According to Holt (2021), applying biochar decreased the toxicity of aluminum to soil microbiota and plant roots.

Biochar can restore farmed soils, especially when taking into account the environmental problems brought about by heavy metal pollution of arable soils. Using biochar as a soil amendment is an inexpensive, green technology that improves crop yield, makes vital nutrients more accessible, and lowers mobility and bioavailability of heavy metals (Giudicianni *et al.* 2013). Consequently, there is a decreased risk to the public's health when eating crops grown in fields that have been treated with biochar. The additional biochar can also be used as an organic fertilizer to increase crop yields. This review paper centers on the advantages of adding biochar to the soil to increase its productivity potential, decrease the uptake of toxic metals by plants, and ultimately enhance crop production potential.

BIOCHAR PRODUCTION

Thermochemical conversion is one technique that has gained popularity recently for turning biomass into biochar. A range of techniques, such as pyrolysis, gasification, torrefaction, hydrothermal, and carbonization are involved in biochar production. However, among the methods mentioned above, pyrolysis is the most frequently used. Pyrolysis usually produces gas and bio-oil in addition to biochar (Pang, 2019). Pyrolysis is the process of thermally breaking down organic compound at a temperature between 250 and 900 °C in an aerobic environment. The process of pyrolysis transforms biomass into new, highly valuable products like bio-oil, syngas, and charcoal (Osayi *et al.* 2014).

During pyrolysis components like hemicellulose, cellulose, and lignin undergo reaction mechanisms that include fragmentation, depolymerization, and cross-linking, resulting in products that can be in liquid, solid, or gaseous state (Yaashika *et al.*

2020). The gaseous products are carbon monoxide, carbon dioxide, hydrogen, and syngas while the solid byproducts include bio-oil and charcoal. A range of reactor designs, such as wagon reactors, paddle kilns, and agitated rotating kilns, are used to produce biochar (de Jong and Gosselink, 2014; Nanda *et al.* 2016). The controlling parameter that governs the efficiency of the process is temperature. The rate at which biochar is synthesized is also affected by pressure, residence time, and heating rate (Lin *et al.* 2016). When the temperature is changed yield of biochar declines while that of syngas increases; the yield varies based on the type of biomass used (Wei *et al.* 2019; Muh *et al.* 2021). Since cellulose, hemicellulose, and lignin make up the bulk of the biomass, such compounds must undergo various reactions (Giudicianni *et al.* 2013).

Cellulose decomposition

Cellulose decomposition is broken down by lowering the degree of polymerization, which requires two steps of reactions. First, through moderate pyrolysis, which necessitates breaking down of cellulose over a longer residence time with a lower heating rate; and second, through rapid pyrolysis, which quickly volatilizes to produce levoglucosan at a high heating rate (Shen *et al.* 2011). To make hydroxymethyl furfural, levoglucosan is dehydrated. This compound can then be broken down to produce liquid or gaseous compounds like syngas and bio-oil, that's how biochar is made. Furthermore, the hydroxymethyl furfural can undergo several steps, including condensation, aromatization, and polymerization, to produce solid biochar (Collard and Blin, 2014).

Hemicellulose decomposition

The breakdown of hemicellulose has a close similarity to that of cellulose. To create oligosaccharides, depolymerization takes place. For the production of biochar or other bioproducts like syngas and bio-oil, this process goes through several phases, such as decarboxylation, intramolecular, rearrangement, aromatization, and, depolymerization (Huang *et al.* 2013).

Lignin decomposition

When comparing lignin's breakdown to that of cellulose and hemicellulose, it is distinct and more intricate. To produce free radicals, the β-O-4 lignin connections have to break down. Decomposed compounds can develop as a result of the generated radicals trapping protons from other species. Moving on to other molecules, the free radicals conduct chain propagation (Mu *et al.* 2013; Wu *et al.* 2023).

3. FACTORS THAT DETERMINE PROPERTIES OF BIOCHAR

Feedstocks

The biomass or feedstocks dictate the characteristics of biochar. Composed of biological, organic, or inorganic components that were formerly a part of living things, biomass is a complex solid substance. Biomass comes in two varieties: biomass that is woody and biomass that isn't (Victor *et al.* 2025; Luciana *et al.* 2025). Woody biomass is characterized by low moisture content and waste products, high density, and calorific value for example forestry and tree residues (Huang *et al.* 2012; Ilomo *et al.* 2025; Tripathi *et al.* 2016). Animal waste and solid residues from industry and agriculture are examples of non-woody biomass, which is distinguished by low density and calorific value, significant moisture content, and high debris. The moisture content of both types of biomasses has a major impact on biomass production (Jafri *et al.* 2018). Water vapor and liquid water that seep into the biomass's pores are among the different moisture contents found in the biomass. The char yield will be significantly impacted by the high moisture content in the biomass because it will require more energy to reach the pyrolysis temperature (Tomczyk *et al.* 2020). Low moisture encourages the production of biochar because it will shorten the longevity and quantity of heat energy needed for pyrolysis. Therefore, compared to situations where biomass has a high moisture content, this is more economically feasible (Zaman *et al.* 2017; Sakhiya *et al.* 2020; Riziki *et al.* 2024).

Carbonization temperature

For pyrolysis to effectively convert biomass into biochar, temperature is the primary determinant. At extreme temperatures in an oxygen-free atmosphere, this thermal degradation process is greatly encouraged. Depending on the conditions at hand, pyrolysis cycles fall into one of three basic categories; firstly, slow pyrolysis followed by moderate pyrolysis, and the last is rapid pyrolysis that needs the heat anergy of, 300 °C, and 500 °C and > 500 °C respectively. The physicochemical properties and structure of biochar are determined in large part by the carbonization temperature. According to Dhyani and Bhaskar (2018), these physiochemical characteristics include functional groups, surface area, elemental components, and pore structure. Higher temperatures affect these qualities because of the rise in volatiles.

Residence time

When the residence time is extended at low pyrolysis (300 °C) temperature, the yield of biochar will gradually decline. Alongside this will be a reformist in pH generated quantity of biochar for iodine adsorption. However, longer residence times at high pyrolysis temperatures (600 °C) probably have less of an effect on biochar yield or pH, however, they do reduce the volume of iodine that biochar can adsorb (Liang *et al.* 2016).

Pre-treatment of biomass

Biochar properties are highly influenced by the biomass's pre-treatment by combining the various ingredients and lowering the particle size of the biomass. A mildly acidic solution is used to soak pine wood as a sample of biomass pretreatment (Xu *et al.* 2017). Metal doping and nitrogen presence influence the synthesis of biochar, whereas steaming or soaking can change the elemental composition and properties of biochar. Baking can decrease oxygen and moisture content while increasing carbon content (Mishra *et al.* 2023). Biochar production can also be affected by mineral composition like chlorine concentration and soluble bases. This can increase consumption and biochar production (El-Naggar *et al.* 2019).

BENEFITS OF BIOCHAR AS A SOIL AMENDMENT

Regulates soil temperature

It has been established that using biochar helps to control the temperature of the soil. The synergistic interaction between variations in soil reflectance and thermal conductivity may form the basis for this regulatory capability (Fig. 1). According to Chang *et al.* (2021), biochar application in the soil was negatively correlated with soil temperature. There was, nevertheless, no discernible difference between the groups. Zhang *et al.* (2013a) showed that

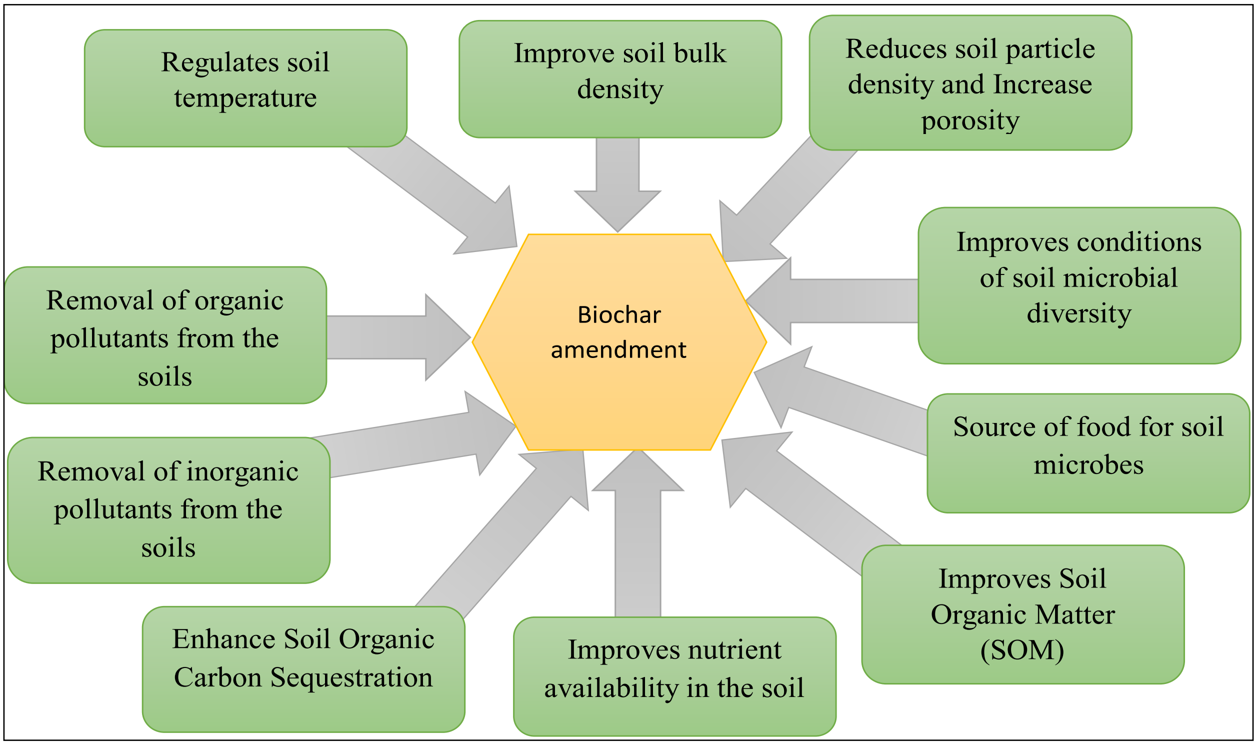

Fig. 1: Benefits of biochar amendment in agricultural soil

increasing the rate of biochar leads to the dramatic fall of thermal conductivity up to 7.5% with 9.0 Mg ha^{-1} yr^{-1} of biochar addition. According to Zhang *et al.* (2013b), biochar will lower soil temperatures when it is applied to warmer soils and vice versa by ± 0.4 °C and ± 0.8 °C during the day and at night, respectively.

Improve soil bulk density

Biochar application enhances the soil's characteristics more significantly in sandy soils as opposed to clayey soils (Glab *et al.* 2016). Moreover, the research conducted by Blanco-Canqui (2017) found that biochar lowered the bulk density of loamy sand soil more than in sandy soil. Reducing the size of the biochar particles enhances water retention but might additionally reduce saturated water flow (Mwadalu *et al.* 2024). It was later determined that adding biochar to soil increased its porosity by 14–64%, and decreased its bulk density by 3–31% (Table 1).

Table 1: Effect of biochar on the soil bulk density in 0-15 cm soil under different feedstock types and soil types

Soil type	Time	Feedstock type	Temp. (°C)	Biochar rate	Bulk density (Mg m^{-3})
Silica sand	NA	Mesquite	400	0%	1.62a
				2%	1.45b
				4%	1.34c
				6%	1.28d
				8%	1.2e
				10%	1.11f
Sandy loam	6 months	Rice husk	600	0%	1.41b
				0.10%	1.31cd
				0.50%	1.28de
				1%	1.24e
Sand	6 months	Rice husk	600	0%	1.45a
				0.10%	1.39b
				0.50%	1.32c
				1%	1.27c
Loam	4 years	Peanut shells	300-350	0 Mg ha^{-1}	1.36a
				28 Mg ha^{-1}	1.31b
Clay loam	2 years	Corn residue	400	0 Mg ha^{-1}	1.35a
				10 Mg ha^{-1}	1.3ab
				20 Mg ha^{-1}	1.24b
Silty clay loam	3 months	Wheat bran	400	0 Mg ha^{-1}	1.07a
			800	14 Mg ha^{-1}	0.93b
			1200		0.96b

Source: *Modified from Blanco-Canqui (2017).*

The physical nature of the soil greatly impacts the accessibility of air and water in the soil, the impact of biochar on soil physical qualities has a direct influence on plant root growth. It may also impact the soil's capacity to retain cations, adjust to pH changes, and react to water. It may also have an impact on the soil's aggregation, dynamics, and permeability during expansion (Chang *et al.* 2021; Baiamonte *et al.* 2011).

Reduces soil particle density and Increases porosity

Although particle density is typically disregarded in standard soil testing and characterization, it is nonetheless significant to note that it has a direct effect on several soil parameters, most notably soil porosity. It affects further features like particular surface area, thermal parameters, and sedimentation (Carter and Bentley, 2016). Particle density of biochar is modest ranging between 1.5 and 2.0 g cm^{-3}. Nevertheless, the non-amended soils had particle sizes ranging from 2.4 to 2.8 g cm^{-3} (Suliman *et al.* 2017). As a result, the soil particle density is reduced following the application of biochar and increases the soil porosity. The porosity of the soil increases significantly through the application of biochar that contains no more than or equal to 60% carbon (Suliman *et al.* 2017). Githinji (2014) conducted a laboratory experiment using loamy sand on the impact of biochar on soil porosity. The results showed a linear decrease in particle density (R^2 = 0.9) as biochar application at 100% can minimize particle density from 2.62 to 1.6 g cm^{-3} (Fig. 2).

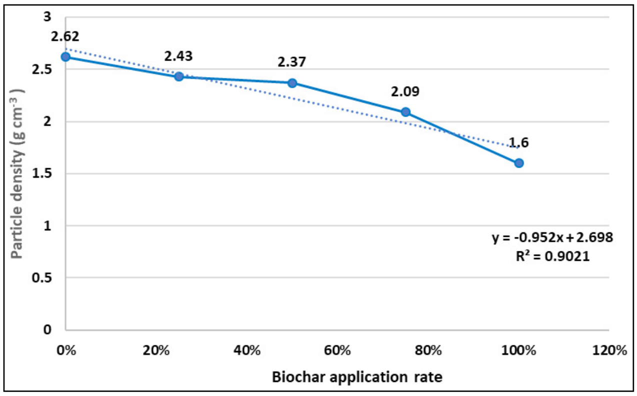

Fig. 2: Impact of biochar on soil porosity

Adding biochar to the soil increased its porosity from 2 to 41%. It was discovered that application of biochar amendment was directly correlated with an increase in porosity. However, as it was the case with bulk density, the effect of enhanced porosity caused by the application of biochar was more noticeable in the macropores or coarse-textured soils than in clayey soils (Blanco-Canqui, 2017). Also, decreased soil parking, greater interaction of mineral particles, and decreased bulk density have been reported to be the root cause of the improvement in soil porosity following biochar application (Obia *et al.* 2016). Conversely, Esmaeelnejad *et al.* (2017) observed that soil porosity was not impacted by applying wheat bran pyrolyzed at 800 °C, however, it was discovered that applying the same wheat pyrolyzed at 1200 °C increased soil porosity. Hence, the experiment revealed soil porosity was improved following the incorporation of biochar. Biochar enhances soil porosity, which can benefit the flow of gaseous substances, heat, and water in the soil (Garg *et al.* 2021; Arvidsson, 1999). The greater overall porosity and lower bulk density, nevertheless, might not always be advantageous for plant growth, thus this must also be taken into attention (Andrenelli *et al.* 2016).

Improves conditions of soil microbial diversity

By giving soil microbial communities greater room to grow, biochar helps to increase the density and biodiversity of these communities (Rasul *et al.* 2022). According to Andrenelli *et al.* (2016), the microorganisms residing within the biochar structure are actively producing polysaccharide compounds that have the potential to improve soil aggregates, hence enhancing the overall health and condition of the soil. Biochar acts as a protective shield for the soil biome in dry soil due to its nature of having a large surface area, which promotes the expansion of said community (Kuzyakov *et al.* 2009; Shaheen *et al.* 2019; Sahoo *et al.* 2024). In general, biochar influences the biological characteristics of the soil, such as microbial biomass, macrofaunal activities, and nitrogen-cycling enzymes (Graber *et al.* 2011). According to other different studies, high-frequency biochar addition tends to stimulate latent soil bacteria, leading to an upsurge in microbial respiration. Moreover, once inside the soil it will typically give a very hospitable environment for the microbial communities because of its porous nature (Knicker 2007; Hamer *et al.* 2004). Moreover, biochar will use sorption to lessen the harmful components' bioavailability (Li *et al.* 2017). According to Paz-Ferreiro *et al.* (2016), the combination of biochar with labile components that typically exhibit biocidal activity may also stabilize the biotic breakdown occurring in the soil.

Source of food for soil microbes

Even though microbes do not use biochar as a source of energy, charcoal has been reported to undergo microbial decomposition in early research conducted in the 20th century. According to certain research, biochar begins to mineralize as it breaks down (Skjemstad *et al.* 2002). Following the addition of the biochar, higher respiration rates were observed. After adding biochar to the soil, there is an initial flush of carbon mineralization. Biphasic patterns of biochar mineralization indicate that the condensed aromatic ring structures are degrading slowly to negligibly levels after the labile or volatile components of the biochar are degraded rapidly (Fierer *et al.* 2003).

Knicker *et al.* (2008) state that biochar decomposes differently from other forms of natural char. It is unlikely that volatiles will recondense because volatilization of organic compounds will occur at temperatures of between 400 and 500 °C since the oxygen available for the breakdown of natural chars is limited. When biochar is added to the soil, integrated organic carbon (OC) can be released into the soil as a source of food for microbes through mineralization process (Bruun *et al.* 2008). According to Kuzyakov *et al.* (2009), the kind of raw material used to make the biochar determines how much integrated organic carbon is present. For instance, the rate at which ryegrass biochar was incorporated into microbial biomass varied from 1.5 to 2.6% after 624 days. This confirms the biphasic breakdown pattern of biochar and shows the limited sustenance that bacteria can obtain from it even after a prolonged incubation period.

Many types of fungi that are saprophytic, use biochar as their primary source of nourishment. The ability of the fungi to release extracellular enzymes that react with various forms of biochar makes this possible. Certain members of the phylum Basidiomycota, *Nematoloma frowardii*, and *Clitocybula duseni* are attributed to this characteristic. It was also found that, in addition to biotic factors, some abiotic processes, like chemisorption and carbonate dissolution, influence the rate of mineralization.

Research by Jones *et al.* (2011) and Spokas *et al.* (2009), revealed the carbonate production during the pyrolysis process which dissolved abiotically to the soil microbes when biochar was added to the soil. Furthermore, when the soil is treated with biochar that has a significant carbonate content, the initial C-respiration will be larger than whenever the inserted biochar included fewer levels of carbonates (Bruun *et al.* 2008).

Improves Soil Organic Matter (SOM)

According to Kolb *et al.* (2009) and Cross and Sohi (2011), biochar effects on the SOM depend on the pre-existing SOM and how it interacts with the microbial community. For example, adding biochar to the soil containing very little SOM will result in a significant increase in biomass and microbial respiration (Whitehead *et al.* 201). Biochar addition to the soils with low SOM, not only increases microbial habitat and accessible C but also makes the soil bacteria in these types of soils more nutrient-adapted than in soils with high SOM (Dignac *et al.* 2017). Applying biochar to SOM-rich soils will boost microbial biomass, albeit not as much as in SOM-deficient soils. Furthermore, it was demonstrated by Cross and Sohi (2011) that bare fallow soils, which had higher resistant SOM pools than arable and grassland soils, respired more biochar-C. This implies that the rate at which carbon mineralization occurs is determined in large part by native SOM.

Improves nutrient availability in the soil

According to Laird *et al.* (2010), biochar has a high porosity that enhances its ability to bind soil and permits greater cation and anion binding. Also, high porosity provides soil microbes with lots of space (Atkinson *et al.* 2010). Moreover, biochar raises the pH of the soil, which greatly increases the amount of phosphorus and potassium that are available for uptake by microorganisms and plants (Toková *et al.* 2020). Liang *et al.* (2006) state that the oxidation of aromatic carbon, which produces carboxylic groups and increases soil CEC, always occurs after the biochar application. The increase in CEC is directly correlated with soil fertility because nutrients are held in the soil and are less likely to be lost through leaching (Emmanuely *et al.* 2023). When highly oxidized organic matter is incorporated into the biochar, the outermost layer loses its negative charge and becomes negatively charged. However, a similar study demonstrated that biochar impacted soils with sand by increasing the levels of soil CEC and soil fertility (Krishna *et al.* 2024; Ajayi *et al.* 2017; Zhang *et al.* 2021; Ray *et al.* 2025).

Enhance Soil Organic Carbon Sequestration

Soil carbon (C) is responsible for several soil processes such as retaining and infiltrating water, producing biomass, storing carbon, and storing nutrients (Chenu *et al.* 2019). A crucial determinant of the productivity of soil is soil organic C. At a depth of one meter in the soil, the SOC pool is equal to twice the atmospheric C stock. It follows that even a slight rise in SOC has an impact on the atmospheric supply (Dawson and Smith 2007). Different parameters including soil properties, climate, and agricultural practices, are said to have an impact on the rate of decomposition of SOC (Lal, 2018). The soil carbon stocks may be depleted as a result of certain agricultural practices, such as frequent planting of crops with shallow roots and high soil disturbances (Sanderman *et al.* 2018). Furthermore, a substantial contribution to the maintenance and growth of SOC stocks is made by inoculating the soil with bacteria that may act on soil organic matter (Whitehead *et al.* 2018; Dignac *et al.* 2017).

Biochar is thought to be a sustainable method of sequestering carbon (Wang *et al.* 2016; Whitehead *et al.* 2018). This is because it facilitates transportation and storage of carbon in carbon pools with a long half-life, which lowers the overall atmospheric CO_2 concentration. Biochar's ability to sequester carbon is determined by its ability to mineralize SOC and its soil stability. Recently, some research has been done on the possibility of using biochar to both sequester and lower atmospheric carbon dioxide levels and highlighted the robustness, longevity, and high C content of the biochar (Tsolis and Barouchas, 2023; McHenry, 2009). Additionally, biochar incorporation is a soil management technique that offers several advantages on the physio-chemical features of the soil and directly increases carbon sequestration. Moreover, biochar has a high organic matter and nutrient composition, which makes it a highly nutritious crop (Ye *et al.* 2019; Chen *et al.* 2023; Okareh and Gbadebo, 2020). According to Thies *et al.* (2009), priming is the term used to describe the alteration in native SOC mineralization following SOC incorporation. Positive priming occurs when the native SOC mineralization increases, whereas negative priming occurs when the mineralization decreases following the application of the biochar (Zimmerman, 2010).

One of the key mechanisms influencing the exchange of carbon between the soil and the atmosphere is the mineralization of SOC, which is triggered by the supply of biochar in the soil. Nevertheless, the application of biochar influences the native SOC's mineralization rate (Thies *et al.* 2009; Chen *et al.* 2021; Wang *et al.* 2016). While "negative priming" results in decreased SOC mineralization, "positive priming" increases native SOC mineralization. The rate of mineralization brought on by the presence of biochar has effects, which are categorized as negative and positive priming effects (Singh and Cowie, 2014; Wendt and Hauser, 2013). Priming has been classified as having "positive priming effects," "negative priming effects," and "no effects" in other literary works. Various soil types and variations in the properties of the biochar are said to be the cause of the variations in the priming effects (Yang *et al.* 2022; Wiesmeier *et al.* 2019). Conversely, priming effects are more closely associated with the features of biochar, such as pH, organic carbon content, the presence of microorganisms, composition, and structure, and may result from the integration of many pathways (Table 2).

Removal of inorganic pollutants from the soils

Many types of inorganic contaminants typically contaminate the soil when they are present in larger amounts and pose serious risks to humans as well as other living things and organisms (Zhang *et al.* 2013a). These hazardous substances are the end product of either industrial processes or solid and/or liquid municipal garbage. Copper, cadmium, zinc, nickel, lead, and mercury are a few examples of extremely poisonous and cancer-causing metals (Mishra *et al.* 2019; Qiu *et al.* 2022). Because of its various functional groups, including its high organic carbon and porous nature, low-temperature-produced biochar has the potential of absorbing inorganic pollutants form the soil.

Table 2: Priming effect of biochar addition to soil

Priming (+)	**Source**	**Priming (-)**	**Source**
When microbial activity is enhanced	Zimmerman *et al.* (2010)	Increased soil accumulation did not affect the SOC	Hernandez-Soriano *et al.* (2016)
Increasing soil fertility which also increases microbial population growth	Paetsch *et al.* (2018)	The availability of carbon to soil microbes is limited due to the absorption of organic matter by biochar.	Eggleston *et al.* (2006)
To better soil aeration resulting from the incorporation of biochar to sandy soils which increased SOC	Liu *et al.* (2016)	When toxic elements are present in the biochar, microbial activities are inhibited	Palansooriya *et al.* (2019)
Application of biochar amount ≤15% (w/w) to the soil.	Han *et al.* (2022)	When the root exudation and incorporation occur after the application cause negative priming SOC	Weng *et al.* (2018)
When biochar from manure and crop residues is produced at low pyrolysis temperatures most constructively contributes to priming SOC	Singh and Cowie (2014)	Biochar application rate from 0.4 to 1.9% (*w/w*) to the soil.	Abbruzzini *et al.* (2017)
Three months after the incorporation of the biochar, the effect was not significant while after six months a significant effect was recorded.	Han *et al.* (2022)		
Natural priming experienced a positive priming initiation effect when biochar was produced at 300 °C, while a negative priming effect was experienced at 500 °C	Lu *et al.* (2021)		

By exchanging ions, the heavier poisonous metals are typically eliminated, due to the adsorption of the porous structure by biochar (Abbas *et al.* 2018). Furthermore, biochar was found to have a high heavy metal adsorption effectiveness when examined utilizing the SEM, FTIR, TEM, and XRD techniques. It was discovered in an experiment assessing biochar's ability to immobilize heavy metals that biochar has a high potential for doing so (Abbas *et al.* 2018).

Furthermore, it was discovered that soils with biochar incorporation had lower levels of lead, copper, and cadmium as compared with soil without biochar. In addition to animal waste and sewage sludge, other biochar raw materials including agricultural wastes like maize cobs, corn cobs, sugar beet, soybean straw, and switchgrass have been used and shown to be effective in lowering heavy and toxic metals (Liang *et al.* 2021). Because of its significant attraction for OH and COOH functional groups, it has been observed that the presence of these groups facilitates the removal of copper. Other factors like the pH of the soil and the kind of biomass, affect the removal of heavy metals primarily (Ramrakhiani *et al.* 2016; Moses *et al.* 2021). The studies conducted by Yaashika *et al.* (2020) found that the dosage of the biochar also affects how well efficiency metals are removed (Table 3).

Table 3: Adsorption of heavy toxic metals by biochar and their removal efficiency

Heavy metal	Material used	Biochar Dosage (%)	Removal efficiency (%)
Cd^{2+}	Chicken manure	5	93.5
	Rice straw	40	93.6
	Tree back	10	99
	Sludge	8	99.9
	Rice straw	5	100
Pb^{2+}	Sugarcane straw	5	50
	Sludge	5	51.2
	Soybean stover	20	90
Zn^{2+}	Hardwood	5	56.7
	Corn straw	5	67
U	Switchgrass	0.5	90
Cr	Sugar beet tailings	0.8	88.5

Source: *Modified from Yaashika et al. (2020).*

Removal of the organic pollutants from the soil

The chemicals used to control pests and diseases, such as herbicides, insecticides, nematicides, and fungicides including atrazine, simazine, and carbofuran, end up in the soil and water as residues from agricultural practices (Hassan *et al.* 2020; Gautam *et al.* 2016; Mohammad *et al.* 2025; Sairaam *et al.* 2023). Other organic pollutants comprise pharmaceuticals and antibiotics like acetaminophen, tetracycline, ibuprofen, sulfamethazine, and tyrosine; industrial waste chemicals like polycyclic aromatic hydrocarbon, catechol, pyrene, phenanthrene, and anthracene, naphthalene and organic compound that can vaporize including furan, butanol, benzene, and trichloroethylene (Mondal *et al.* 2016; Yaashika *et al.* 2020; Nungula *et al.* 2023). It was discovered that the amount of added biochar to the soil increased the degree of organic pollutant adsorption. Additionally, it was discovered that as the concentration of biochar grew, increase the rate at which carbofuran was degraded and adsorbed. Adsorption is increased by the quality of the functional groups and carboxylic groups (Xiong *et al.* 2019).

Amalina *et al.* (2023) discovered that the relationship between organic contaminants and biochar dictates the biochar's capacity to eliminate them. Pore diffusion, H-bonding, hydrophobicity, physisorption (electrostatic attraction/repulsion), and chemisorption (electrophilic contact) are some processes for organic contaminants removal. These processes occur in the presence of functional groups like OH and COOH. Partitioning, chemical transformation, and biodegradation are possible additional mechanisms at play. Zhu *et al.* (2017) revealed the ratio of applied biochar, biomass nature, pH, temperature, and pollutants are possible variables that affect how biochar interacts with organic pollutants. In an experiment to evaluate the removal and uptake of organic pollutants by plants, the organic pollutants were found to decrease in a biochar-amended soil, but the concentration of biochar also increased the removal of the pollutants when compared to unamended soils (Gupta *et al.* 2022). The efficiency in removing pollutants is accelerated by its particle size; smaller biochar particles are said to be more effective in eliminating pollutants while simultaneously requiring less time to remove them (Jin *et al.* 2022). Also, Liu *et al.* (2018)

found that factors such as soil pH can influence the breakdown and adsorption of contaminants.

CONCLUSION

Since biochar possesses better properties than ordinary sources of soil organic matter, it is highly recommended for use by farmers given that it significantly improves most of the properties resulting in increased soil fertility and high agricultural productivity. Moreover, it plays a key role in the decontamination or removal of both organic and inorganic pollutants thus minimizing the chances of the plants to take up the pollutants. On the other hand, there is a need to solve the negative consequences associated with biochar application like the decline of crop yield due to the sorption of water, nutrients, and pesticides. Such sorption reduces the efficacy and contamination of soil with heavy toxic metals. This will make biochar a more sustainable amendment for agricultural productivity.

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